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DESIGN AND DYNAMIC TESTING OF AN ULTRA-HIGH  
ACCURACY SATELLITE STABILIZATION AND CONTROL SYSTEM  
FOR THE ORBITING ASTRONOMICAL OBSERVATORY

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Introduction

The Orbiting Astronomical Observatory, or the OAO, is the largest scientific satellite now under development for the National Aeronautics and Space Administration. Figure 1 is an artists conception of the OAO in orbit.

The OAO program objective is the launching of a series of very highly stabilized unmanned observatories beginning in 1964. Each satellite will weigh over 3500 pounds and will contain approximately 1000 pounds of advanced scientific equipment. Initial launches will investigate the ultraviolet emissions of various stars, nebulae, and interstellar matter; later experiments will likely investigate other regions of the electromagnetic spectrum.

Several facets of the satellite's design, as well as various aspects of scientific program, have already been discussed in technical treatises and magazine articles; however, substantial details of the design and operation of the OAO's stabilization and control system have not been published prior to this meeting. The stabilization system for the OAO is designed to meet accuracy requirements which are orders of magnitude more demanding than those of any previous specification. The OAO may well be the most highly stabilized satellite now under development. Design of the OAO stabilization system is now well advanced. Models of all components have been constructed and under test for some time. Final qualification tests, which will verify that the system has met its design objectives, will begin shortly. At this time we will discuss the spacecraft design and present a detailed description of the program and facilities for dynamic testing of the OAO.



### System Design

The functions of the OAO's stabilization and control system are threefold:

- (1) First, the system must stabilize and orient the spacecraft following booster separation.
- (2) Second, the system must be capable of slewing the satellite to point to any desired location on the celestial sphere as dictated by the scientific objectives of the mission.
- (3) Lastly, the stabilization system must be able to maintain given attitudes with the required precision for long periods of time.

In order to perform these functions, a system design has been developed which employs a variety of sensors and actuators, as shown in Figure 2. The sensors, which provide the necessary information related to OAO orientation in space, include star trackers (of two types), solar trackers, a TV system, rate gyros, and magnetometers. The actuators, which are used to torque the observatory, include both fine and coarse inertia wheels, a gas jet system, and a magnetic torquing system. With each of the sensors there is, in general, an associated electronics unit called a "signal processor"; and with each of the actuators there is, in general, an associated electronics unit called a "controller". Also important to the stabilization system is a "programmer", a logic unit which provides proper sequencing for the control system.

Figure 3 is a functional block diagram of the stabilization system, indicating the various components of the system. The performance requirements of each of the units, as well as the individual functions they perform, will become evident as we discuss the system operation in some detail.

### Initial Stabilization and Orientation

The initial stabilization and orientation mode begins immediately following separation from the booster and ends when the OAO's optical (longitudinal) axis is aligned with the sunline to within  $\pm 0.025$  degree of arc and the star trackers have locked onto their guide stars. This operation is performed in several phases. The first phase employs the components shown in Figure 4 and is essentially one in which the random tumbling rates following booster separation are reduced to some desired threshold and coarse solar acquisition and orientation is completed. As indicated in the figure, the rate gyros, one aligned along each control axis, and coarse solar sensors are utilized in this sequence to control the OAO's gas jet system. The gyros are spring-restrained single-axis rate gyros having a capability to null body rates to within 0.03 degree per second.

The OAO's coarse solar sensing system consists of eight "coarse" sensors, four mounted so as to provide displacement information relative to the pitch axis and four mounted about the yaw axis as shown in Figure 5. Each sensor has a hemispheric field of view, with the result that the coarse sensing system provides bi-axial control signals for the OAO's pitch and yaw axes over the entire celestial sphere. The solar sensors have silicon photosensitive elements. Deep red filters are attached which pass radiation between 0.6 and 1.1 microns, peaking at 0.8 microns. The actual outputs of the sensors are shown in Figure 6. An interesting feature of the OAO's design is that the outputs of rate gyros and the solar sensors are combined in the sensor signal processor during this initial phase. Gains are adjusted so that a spacecraft angular rate of 0.5 degree per second produces a gyro output signal equal to the saturation output of the coarse solar sensors which occurs at  $\pm 5.50$  degrees. Following booster separation, the high thrust

jet system will reduce the initial spacecraft rates to  $\pm 0.5$  degree per second regardless of the initial angular error. When the spacecraft rates have been reduced to this value, the combined signal will continue the decelerating jet torque if the satellite attitude is outside of the  $\pm 5.5$  degree proportional range of the sensor and the error angle is increasing. If the error angle is decreasing, the combined signal will be zero and the satellite will coast into the sensor's proportional range. Then, as the sensor output decreases, the rate gyro signal will again dominate and command a decelerating torque.

The nitrogen gas jet system which is operative during this period is the OAO's high thrust system. The complete system including both high and low thrust jets is shown in schematic form in Figure 7. Thirty-two pounds of dry nitrogen is contained aboard the OAO in a 3500 psi system. Each of the high thrust jets has a thrust of 0.1 pound, and a torque capability of 0.291 foot pound. For initial booster separation rates of 1.0 degree per second, and with the OAO pointed directly towards the sun, tumbling can be stopped and the OAO turned  $180^\circ$  in approximately 5 minutes of time.

The first phase of the initial stabilization and orientation mode is complete when the spacecraft motion approaches a  $\pm 2$  degree limit cycle operation with a residual rate of 0.03 degree per second. Limit cycling is centered on the sun line with the aft end of the spacecraft pointed directly towards the sun.

Phase 2 of the initial sequence, shown in Figure 8, can now begin.

In addition to the eight coarse solar sensors, the OAO is equipped with a series of eight "fine" solar sensors and a "disable" sensor. The fine sensors and disable sensor or "eye" are all mounted on the aft end of the spacecraft and are precisely aligned with the spacecraft optical axis. The fine sensors have a limited field of view of 10 degrees, while the disable sensor is effective through angles of  $\pm 8$  degrees.

When the disable eye detects the presence of the sun in its field of view and the output of the rate gyro is minimal, the spacecraft programmer automatically switches control of the pitch and yaw gas jets to the fine sensor system. The fine inertial wheels are also activated at this time. During phase 2, spacecraft roll motion is maintained at a low value by outputs from the roll rate gyro. After approximately 13 minutes have elapsed, the spacecraft roll axis is aligned with the sun to within  $\pm 0.25$  degree and all body axis rates have been reduced to  $\pm 0.03$  degree per second.

Phase 3 of the initial orientation phase, shown in Figure 9, is now commanded. The optical axis continues to be controlled to  $\pm 0.025$  degree of the sun, but a bias is introduced into the roll rate output, causing the roll high thrust jets to fire and accelerate the spacecraft about the roll axis to a rate of 0.2 degree per second.

The fourth phase of the initial sequence now begins, and for the first time the OAO's six primary star trackers come into operation. A description of the star trackers is appropriate at this time.

The observatory's six main star trackers are electro-mechanical/optical units consisting of an optical system, light beam modulators, a photo-electrical detector, tracking electronics, gimbal transducers, DC torquers, servo amplifiers, an outer gimbal resolver, a protective sun shutter, and a supporting structure containing a machined reference-mounting surface. The tracker design is illustrated schematically in Figure 10.

The tracker is essentially a photoelectric astronomical telescope mounted on a 2-degree-of-freedom gimbal system. Although employing a single objective mirror; two star images are formed internally by splitting the convergent light into two beams. The beams are modulated by means of two apertured vibrating reeds located in the focal planes of the objective mirror. The reeds are oriented so that their projections are 90 degrees to one another and they

vibrate in the planes of the apertures. The modulated light flux is detected by a photomultiplier. Output signals for operation of the gimbal torquers and for indication of "star presence" and "star tracking" signals are derived by examination of the first and second harmonics of the modulating frequencies. To eliminate possible ambiguities, one reed vibrates at 450 cps while the other operates at 350 cps.

The star tracker telescopes have an effective 1 degree field of view; a gimbal excursion of  $\pm 45$  degrees is permitted about each of the orthogonal gimbal axes. Each tracker is capable of precision tracking of stars having a visual magnitude of two or brighter with an accuracy of 30 seconds of arc. The objective mirrors, made from beryllium, are 3.5 inches in diameter and have an effective focal length of 5 inches. One of the more interesting features of the star tracker is the gimbal transducer. The transducers employed by the OAO are "PHASOLVERS". These are multi-pole shaft-angle to phase-angle transducers whose capacitances vary with shaft angle. The phasolver also phase-shifts a reference signal proportionally to the rotation of the shaft on which it is mounted. Positive null detection of the reference and output signals provide on-off gate pulses for a high frequency counter. The resulting count represents phase shift and is an exact analogue of the shaft displacement. The transducer is formed by printing two sinusoidal metallic patterns on the rim of a glass-bonded mica disc 4.5 inches in diameter. Electrostatic coupling between these patterns is accomplished by means of a rectangular pattern on a second disc in close proximity to the first. As one disc rotates with respect to the other, the capacitance between them varies in a sinusoidal manner. The patterns on each disc are repeated 256 times about each circumference. Thus, every 1.4 degrees of relative rotation, the capacitive coupling goes through a complete cycle. By measuring techniques of an electrical accuracy of no better than 0.1%, accuracy of 5 seconds of arc is attained. To resolve ambiguities arising from the fact that the pattern is

repeated 256 times, a second set of "coarse" metallic patterns is also included on the discs. These patterns vary in capacitance through a single cycle each 90 degrees of mechanical revolution.

Each OAO star tracker can be operated in a "command" mode as well as in a "tracking mode. In the command mode, the tracker can be pointed relative to its own reference axis within 20 seconds of arc. In the tracking mode, the gimbal transducers act as feedback controls in a position servo system.

During phase 3 of the initial stabilization sequence, the trackers operate as follows. Each tracker, while the OAO is rolling about the sunline, is prepositioned (by stored commands) with respect to the spacecraft optical axis, as shown in Figure 11, in such a manner that at one specific roll angle, all six star trackers will simultaneously detect preselected guide stars. Due to occultation effects, it is conceivable that all trackers will not detect stars simultaneously and there is also a distinct possibility that as the observatory rolls about its optical axis, one or more star trackers may detect stars other than the preselected guide stars on a random basis. However, all trackers remain in this command mode or locked gimbal position until the star tracker signal processor receives star presence signals simultaneously from four or more trackers. At that instant, those trackers generating star presence signals are unlocked and allowed to track their guide stars. Spacecraft attitude and control is transferred to trackers at this point. Then, the spacecraft is returned to a zero roll rate condition and the gyros and sun sensors are switched "off".

The final phase of the initial orientation sequence is the mode in which the OAO rolls back to the unique roll angle at which star presence was initially detected and the remaining trackers are unlocked. This operation is accomplished by using the difference between the actual star tracker gimbal angles existing at the completion of the roll rate nulling and the originally commanded angles as error angle signals to the pitch, yaw, and roll fine wheels. When the error

signals have been reduced to zero, the spacecraft's pitch, yaw, and roll axes will all be within 1 minute of arc of the command position. The initial stabilization and orientation sequence is now complete.

To summarize the initial sequence following booster separation, the random tumbling caused by separation action is reduced to a threshold by the rate gyros. Simultaneously, the coarse sun sensing system causes the aft face of the OAO to point at the sun. The fine sun sensors take over and bring the optical axis into alignment with the sun line. Roll about the sun line next takes place. The star trackers are activated and, when they detect stars, operation of the OAO is transferred to star tracker control.

Under the worst conditions, the initial sequence will be completed in 5 hours. The OAO is now ready to begin reorientation maneuvers as required by the experimental equipment.

### Reorientation

The reorientation mode is defined as that mode of operation in which the spacecraft is commanded to change its orientation and perform the required slewing maneuver. The devices involved in this mode, are the coarse inertia wheels, the coarse wheel controllers, the programmer, and the spacecraft digital data processor.

Reorientation is always initiated by a command from the data processor's command storage. The command consists of two signals. One of the signals selects the control axis about which the slewing maneuver is to take place, while the other determines direction of slews. Reorientation is performed in what might be termed a "pseudo-open-loop" fashion. Spacecraft rotation about any control axis is achieved by activating the coarse inertia wheel motor whose axis of rotation is parallel to the desired control axis. The required number of degrees of rotation about the spacecraft axis is related to the number of

degrees of rotation of the coarse inertia wheel by the ratio of the moment of inertia of the spacecraft about that axis, to the moment of inertia of the coarse wheel. The slewing command consisting of the number of wheel rotations required is transmitted to the coarse wheel controller from the command storage. The number of revolutions to be accomplished before torque reversal as well as the total number of revolutions for the entire slew are placed in a register and the wheel accelerated. A magnetic revolution counter enables the rotations to be counted-down in sequential binary fashion. When the number of counts to torque reversal is reached, the polarity of the motor is reversed. This decelerates the wheel and, theoretically, should cause the wheel to stop when the total number of revolutions has been attained. To assure that the motor stops at the proper time, an electro-magnetic brake is activated when the command register has been counted-down to zero and forces the wheel to a complete halt in less than one revolution, thus ensuring that the errors at the end of slew are minimized.

The OAO's command storage unit can store 15 three-axis pointing commands per orbit. The format for commands is shown in Figure 12. Each attitude change command consists of two 32-bit words. The first two bits of each word are for synchronization purposes. Bit 3 of the first word indicates whether the word is a stored command or a command to be executed immediately. Bits 4 through 13 of the first word indicate the command execution time for stored commands. Bits 14 through 20 indicate the command memory address for the command. Bits 21 through 24 denote the class of command (hence the system can decode fifteen other kinds of commands as well as the slewing command). Bits 25 through 27 select the appropriate inertia wheel; the remaining bits in the first word are not used in the slewing commands. Bit 3 of the second word indicates whether the wheel is to rotate clockwise or counterclockwise, while bits 4 through 17 indicate the number of rotations before torque reversal. The total number of rotations before the wheels are braked are contained in bits 18 through 32.

Shown in Figure 13 are a few details of the momentum packages. Each momentum package contains both coarse and fine inertia wheels as well as a rate gyro. One package is installed along each OAO control axis. The package concept was devised to ease the problem of alignment during installation in the spacecraft. The wheels are "inside-out" induction motors. The coarse wheel has a stall torque capability of 32 ounce inches while the fine wheel's stall torque is 2 ounce inches. Total OAO slewing capability is limited by the power available from the OAO's solar arrays and is approximately 300 total degrees per day.

#### Coarse Pointing Mode

The coarse pointing or attitude hold mode is defined as that mode of operation during which the spacecraft is commanded to maintain an arbitrary but predetermined orientation with respect to inertial space, without benefit or a target star along the line of sight of the spacecraft optical axis. The devices used during this mode are shown in Figure 14. In the coarse pointing mode, each tracking star tracker utilizes the telescope error signals to drive the gimbals such as to maintain the telescope line of sight pointing at its guide star. The angles of each star tracker are provided in digital form by the phasolvers mounted on each gimbal axis. The digitizer logic unit accepts the phasolver outputs as well as the command angles from the data processor and, from these, generates error signals in analog form for each of the twelve gimbals. The error signals corresponding to the difference between the commanded and actual angles of the inner gimbal of each star tracker are transformed by resolvers into torque commands to the star tracker gimbal axes.

Generally there are three outputs (one for each of the control axis) from a star tracker and six star trackers. This signal redundancy is averaged in the star tracker signal processor, and the fine wheels are driven in accordance with the average error signal output for each axis. The fine wheel and jet controller

receives the signal processor outputs and commands fine wheel rotation. Using the coarse pointing system, the OAO can be pointed to any desired position within an accuracy of 1 minute of arc. The OAO has been designed to maintain this attitude within 15 seconds of arc for periods of 50 minutes of time.

#### Fine Pointing Mode

The fine pointing mode is defined as that mode of operation in which the pitch and yaw actuator channels are controlled by error signals from a fine error sensor which is an integral part of the experimental optics. Only those experiments requiring accuracies greater than 1.0 minute of arc will be equipped with such a sensor. Operation in this mode is identical to the coarse pointing mode except that pitch and yaw control signals are derived directly from the error sensor instead of from the gimbaleed star trackers. When an appropriate sensor is installed, the OAO can maintain the pointing position within  $\pm 0.1$  second of arc.

#### Momentum Unloading Mode

The OAO in orbit is subjected to a variety of disturbance torques. The most predominant of these is the gravitational torques due to inertial unbalance of the observatory. Figure 15 shows the summation of the predicted torques. In general, these torques act in a symmetric fashions and will require continual acceleration of the fine wheels to maintain any given orientation. Momentum saturation of the fine wheels would thus result except for the fact that the OAO is provided with two separate momentum unloading systems for the removal of accumulated angular momentum. The low level gas jets are the primary unloading system. Each low level jet has a thrust of 0.002 foot pound and a torque capability of 0.00678 foot pound. Firing of the jet is actuated when the fine wheel speed reaches 40% of its maximum speed and a "permission to unload" signal is

available. The wheels are unloaded unconditionally at 85% of maximum speed. The wheels "despin" against the jet torque until 5% speed is reached, at which time the jets are turned off. The system design is such that unloading will occur no more frequently than once every  $1\frac{1}{2}$  orbits.

The second means of unloading stored momentum is the magnetic unloading system. A magnetic unloading processor is used to continually compute the components of the cross product of the angular momentum vector and the earth's magnetic field vector. Currents proportional to the components of the cross-product vector are applied to a set of three permeable-core coils which in turn create a controllable internal magnetic field. The interaction of this controlled field and the earth's field provides the torque which removes momentum from the inertial wheels. The magnetic system will be continuously operative.

#### Boresighted Star Tracker and TV System

The remaining components in the stabilization system are the boresighted star tracker and the TV system. The boresighted star tracker is not gimbaled, but is rigidly attached to a mount along the OAO's optical axis. An image dissector tube is the active element. It employs electromagnetic scanning principles, and is capable of locking onto target stars and providing closed loop control over the fine wheel system in much the same manner as the experimenter's fine error sensor. Electronic offset provisions are provided out to  $\pm 1.5$  degrees, such that the boresighted tracker can be used to offset the OAO through small angles. Hence the boresighted star tracker is a valuable backup to the main star tracker control system.

The TV camera contains a series of reticle lines which, when reproduced on the ground, will enable the ground operator to obtain not only a picture of the sky but a superimposed gridwork. By measuring star displacement with respect to the grid, spacecraft orientation can be obtained with a precision of approximately 5 minutes of arc.

## DYNAMIC TESTING OF THE S & C SYSTEM

One of the major problems in the development of a satellite such as the OAO is that of proving and demonstrating specified system performance under realistic environmental conditions prior to launch. The dynamic testing of any stabilization and control system in a ground environment which accurately simulates the orbital environment is a challenging and difficult task. In the case of the OAO, this testing becomes more complex because of the exceedingly tight accuracy requirements.

To test stabilization systems properly, a dynamic simulator must be employed which can be operated in a precisely controlled environment. To demonstrate that the spacecraft could attain the required accuracy under conditions comparable to those encountered in orbit, it was necessary to design an ultra-precise attitude reference system, which had the capability of measuring attitude to an order of magnitude greater than the specified performance accuracy. A feature of the orbital environment which is most difficult to reproduce on earth is the low static and dynamic friction force. The dynamic friction torque levels which can be tolerated are on the order of 10,000 dyne centimeters, at an angular rate of  $10^{-3}$  deg. sec. At higher levels, the damping effect of these torques becomes so significant as to make an evaluation of the performance of the control system impossible.

The only type of suspension or support having the low friction coefficients desired is an air-bearing. Since a complete, 3-degree-of-freedom simulation of the stabilization and control system operation is required, a spherical air-bearing was designed which supports a platform on which the entire S & C system and all accessory equipment is mounted. An air-bearing produces adequately low friction torques. If not properly designed, it can also generate torques which act as disturbance torques on the system. These torques are caused by the turbine

effect of the air flow around the bearing. Since the disturbance torques expected in orbit will not exceed an average of 2500 dyne-cm, the random torques produced by the air-bearing should be at least one order of magnitude smaller in order not to introduce undesirable excitation terms on the control loop. Preliminary tests on the air bearings designed for the dynamic testing of the OAO, as well as exhaustive tests on a number of smaller air bearings designed for CAO development and for use on other projects, indicate that such low torque levels are attainable.

The air bearing to be used in the Dynamic Test Facility is a 22 inch diameter stainless steel ball which has been polished to a sphericity of less than one ten-thousandth of an inch (see Figure 16).

The socket and pedestal supporting the air bearing are designed to allow the air bearing to rotate freely about the vertical axis while limiting pitch and yaw movements to  $\pm 30$  degrees. The socket incorporates a plenum chamber from which the nitrogen supplied to the air bearing is scavenged. The socket is also of stainless steel, but has an epoxy resin liner which was cast around the finished bearing. An automatic caging mechanism is provided to support the bearing when not in use or in the event of an air supply failure.

The air bearing platform is illustrated in Figure 17. Its dimensions are 109 inches across the arms and 80 inches deep. The total weight is 5000 pounds, and the moments of inertia exactly duplicate those of the flight observatories. The platform is capable of mounting not only the stabilization system, but also is designed to be able to accommodate the entire OAO electronics system, including data processing, communications, and power supply. It is intended that the entire electronics complement of all flight observatories will be mounted on the table and subjected to acceptance tests before installation in the flight structure. To demonstrate convincingly the performance capabilities of the stabilization and control system, the orbital disturbance torque environment must also

be simulated. A typical disturbance torque profile over one orbit was shown on a previous slide. The torques about each of the axes are not equal and are, in general, functions of the spacecraft attitude relative to celestial coordinates. The complete three-axis simulation of the disturbance torque profiles corresponding to any spacecraft attitude requires the ability to apply variable torques about each of the platform axes, up to a level of about 2500 dyne centimeters. A technique applying the disturbance torques to the platform by external means was developed and has been demonstrated on the smaller air bearing table. Essentially, the concept employed was to consider the spherical bearing as the rotor of an induction motor and place a set of three orthogonal wire-wound steel cores in the bearing and thus to generate motor torques. The currents in the windings can be externally controlled and any desired torque profile generated by programming the current flow as functions of time, using analog curve followers. Since the air-bearing is made of stainless steel, the induced currents are low, and distortion of the applied magnetic field caused by the induced currents and by motion of the bearing is negligible. Thus, the disturbance torque generation is essentially uncoupled from the dynamics of the control system and vehicle.

As discussed earlier, an important control system function is the unloading of the inertia wheel momentum by means of a set of magnetic torquing coils which interact with the earth's magnetic field. To demonstrate the effectiveness of this technique, the magnitude, direction relative to spacecraft coordinates, and time variation of the earth's magnetic field which the OAO will encounter in orbit must be simulated in the dynamic test facility. This is accomplished by means of three orthogonal sets of  $17\frac{1}{2}$  foot diameter Helmholtz coils, which surround the simulator platform. Each coil has two sets of windings mounted on it. One set is employed to cancel the ambient magnetic field existing at the simulator, while the second set is used to simulate the orbital magnetic field and its

variation with time. The magnetic field profile is also generated by programming the Helmholtz coil currents as time functions using analog curve followers. The size of the coils is such that the magnetic field at any instant does not vary by more than 0.5 gauss over the entire surface of the simulator platform.

Analytical investigation of the structural and thermal characteristics of the simulator indicated, and experiment confirmed, that disturbance torques, exceeding the capability of the control system to counteract, could be obtained as a result of minute mass unbalance, anisoelasticity, and thermal distortion in the simulator platform. For example, since the platform with all equipment mounted on it weighs approximately 7000 lbs. the center of mass must be within  $10^{-7}$  ft of the center of suspension so that the unbalance torque will be less than 10,000 dyne-cm. The problems of balancing the table, equalizing the thermal expansion and compensating for anisoelasticity of the structure so as to yield reasonably low restoring torques at all table attitudes are so complex that only spot balancing procedures can be adopted. Specifically, the table will be precisely balanced at a particular attitude. All dynamic testing of the fine and coarse attitude hold modes will be performed at that attitude.

Extensive investigations were made of the effect of atmosphere at ambient pressure surrounding the air-bearing and platform. Damping effects due to viscous air drag were found to be small in comparison to the damping factor incorporated into the control loop. Excessive disturbance torques were, however, produced by the unequal heating and thermal expansion of the air in the vicinity of heat producing sources on the platform. Experiments performed on the 10" air-bearing table showed that a 28 watt unbalance in power dissipating elements on the table generated as high as 25,000 dyne-cm of hydrostatic disturbance torque. Since it is estimated that the thermal unbalance cannot be kept below 20 watts on the dynamic simulator, it was decided to enclose the entire facility within a 22 foot diameter aluminum chamber, and to operate at an ambient pressure of 750 microns.

The development of a suitable attitude reference and precision readout system proved to be a difficult task. To simulate all the operational modes of the OAO stabilization and control system, both solar and stellar references are required. The solar simulator presented some exceedingly complex design problems, since a very well defined, uniform source with an intensity approaching that of the sun and a size such as to subtend roughly the same angle as the sun is required to successfully simulate the solar sensing phases of the initial stabilization mode. No existing solar simulator or high intensity carbon arc lamp was suitable for this application. The solar simulator developed for the OAO dynamic test facility employs an optical technique to produce a source of illumination having the required characteristics. Eighteen high-intensity Xenon arc lamps are mounted inside a spherical housing having a highly reflective wall coating. The luminous flux exits from the housing through a 6.5 inch aperture, which represents the actual light source to the solar sensors. It is possible to generate 56% of the solar illumination in the 0.6 to 1.2 micron range.

The stellar reference system consists of a set of five 16 inch diameter high-precision optical collimators mounted inside the chamber. These collimators will simulate stars between magnitudes of -2.0 and -6.0.

To achieve the required precision of platform attitude readout, a two-stage readout system had to be devised. Monitoring of the fine pointing mode requires a readout accuracy of better than 0.1 second of arc. This precision can be attained only through the use of high quality, narrow field electronic autocollimators, using platform mounted, optically flat mirrors as the reflective medium. Since dynamic readout at arbitrary platform attitude is not feasible with these devices, high precision readout will be performed only at the attitude of fine (or coarse) pointing selected for a particular test run.

An all-attitude readout system was developed to determine table attitude to a somewhat lower accuracy during transients of the fine and coarse pointing modes or during reorientation. This system employs 3 sheets of transparent polarized material which are mounted on the platform and serve to polarize the output of three light sources arranged orthogonally to each other on the pedestal of the air bearing. Three sets of servo driven photosensitive detectors are mounted inside the chamber and follow the rotation of the polarizing sheets (and thus of the platform), indicating platform attitude.

The complete dynamic test facility is depicted in Figure 18. The major elements previously described are: (1) the 22 inch diameter air bearing, which is floated in its pedestal on a film of nitrogen continuously fed through a pedestal at low pressure; (2) the air-bearing table, on which are mounted the components under test; (3) collimated light sources which provide simulated stars; (4) Helmholtz coils which simulate the earth's magnetic field at orbital altitudes; (5) the air bearing torquer; and (6) the solar simulator mounted outside the chamber. All of this equipment with the exception of the solar simulator is in the large vacuum chamber which is mounted in turn on a 240,000 pound seismic foundation. Adjacent to the simulator is the control room which will house a duplicate of the central control station to be utilized at the Goddard Space Flight Center during actual orbital operations.

Figure 19 shows the central control consoles for the OAO system. Another part of the central control station is a large digital computer, as well as a smaller computer and a host of data processing equipment.

The facility just described is the ultimate facility intended for use in the OAO program. Several smaller facilities of lesser capabilities have also been employed in the program, notably a 10-inch facility. This latter equipment has been used to conduct dynamic tests on all of the previously described operational modes other than the magnetic unloading mode.

The tests thus far have been on an individual basis. However, in the next few weeks, testing will start on the entire stabilization sequence from booster separation through solar acquisition and orientation, slewing maneuvers to coarse obtaining, and finally to the fine pointing mode.

#### Summary

Summarizing, the OAO stabilization and control system has been designed to what we believe to be the most exacting requirements yet imposed on any satellite. Based on tests of the hardware now in being, we should be able to point the OAO to any position on the celestial sphere with an accuracy of 1 minute of arc and to maintain that position for long periods of time. We should further be able to maintain lock-on to target stars to tenths of seconds of arc. By combining these stabilization accuracies with the information gathering capabilities of astronomical instruments at an altitude of five hundred miles above the earth's surface, we may expect to see the science of astronomy enjoy an unprecedented era of advancement in the next decade.

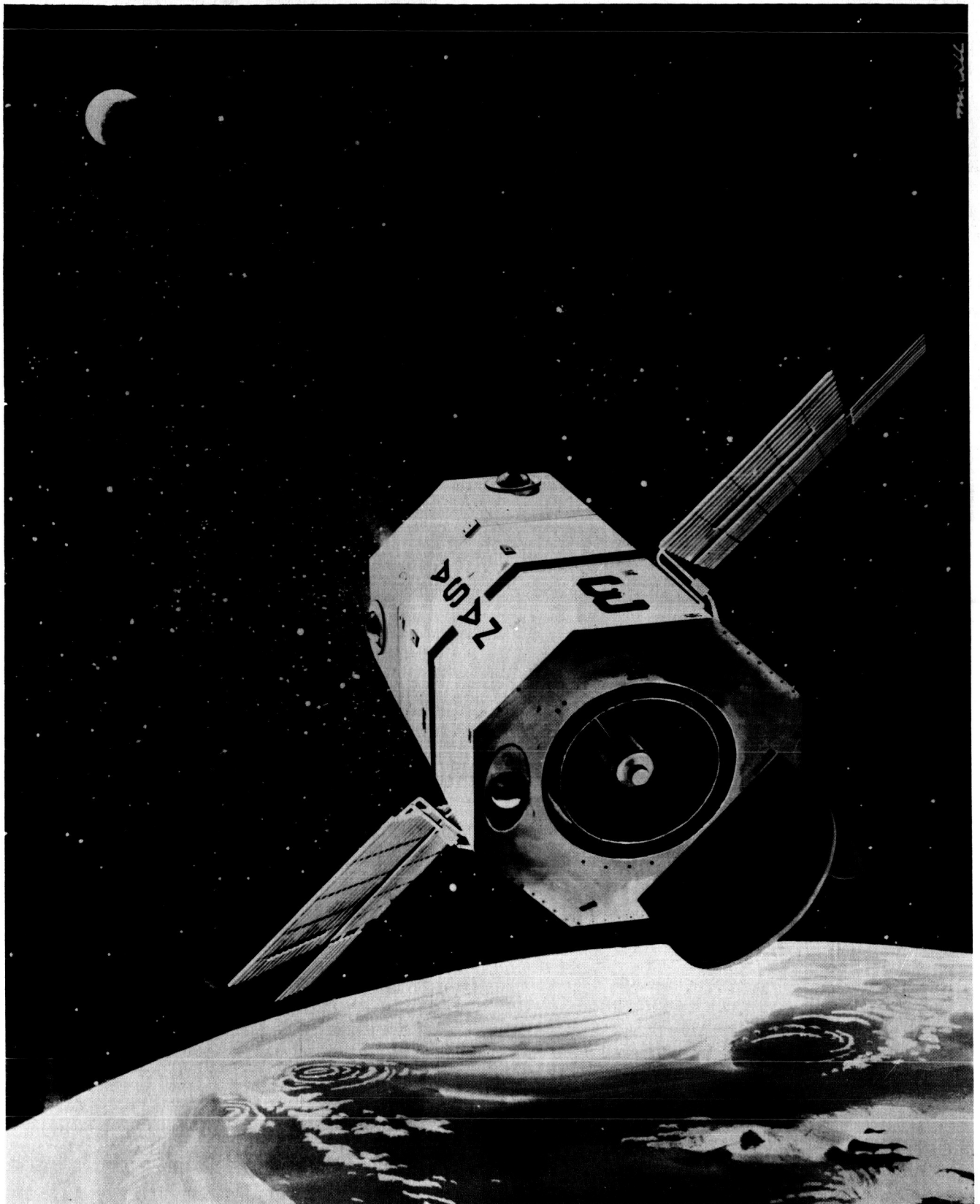


Fig. 1 Artist's Conception of OAO in Orbit

## **SENSORS**

**Primary (Gimballed)  
Star Trackers (6)**

**Boresighted Star  
Tracker**

**Rate Gyros (3)**

**Solar Sensors**

**Coarse (8)**

**Fine (8)**

**Disable Eye**

**Magnetometer**

**Television**

## **ACTUATORS**

**Gas Jet Systems  
High Thrust (2)  
Low Thrust**

**Coarse Inertia Wheels (3)**

**Fine Inertia Wheels (3)**

**Magnetic Torquers (3)**

Fig. 2 Primary Sensors and Actuators for OAO Control System

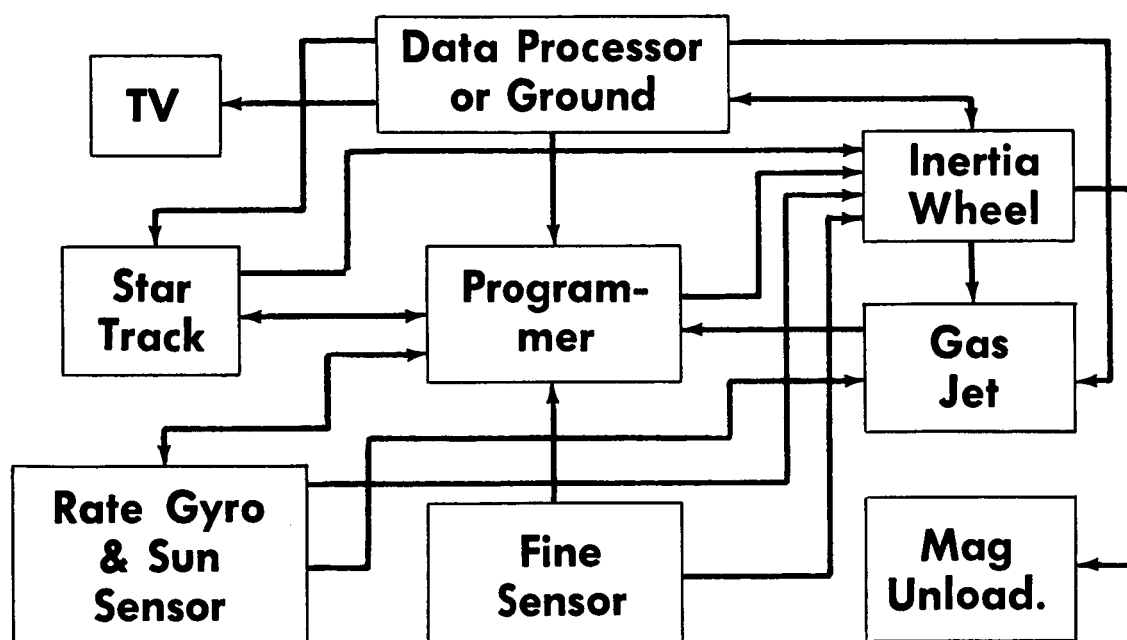


Fig. 3 OAO Stabilization and Control System

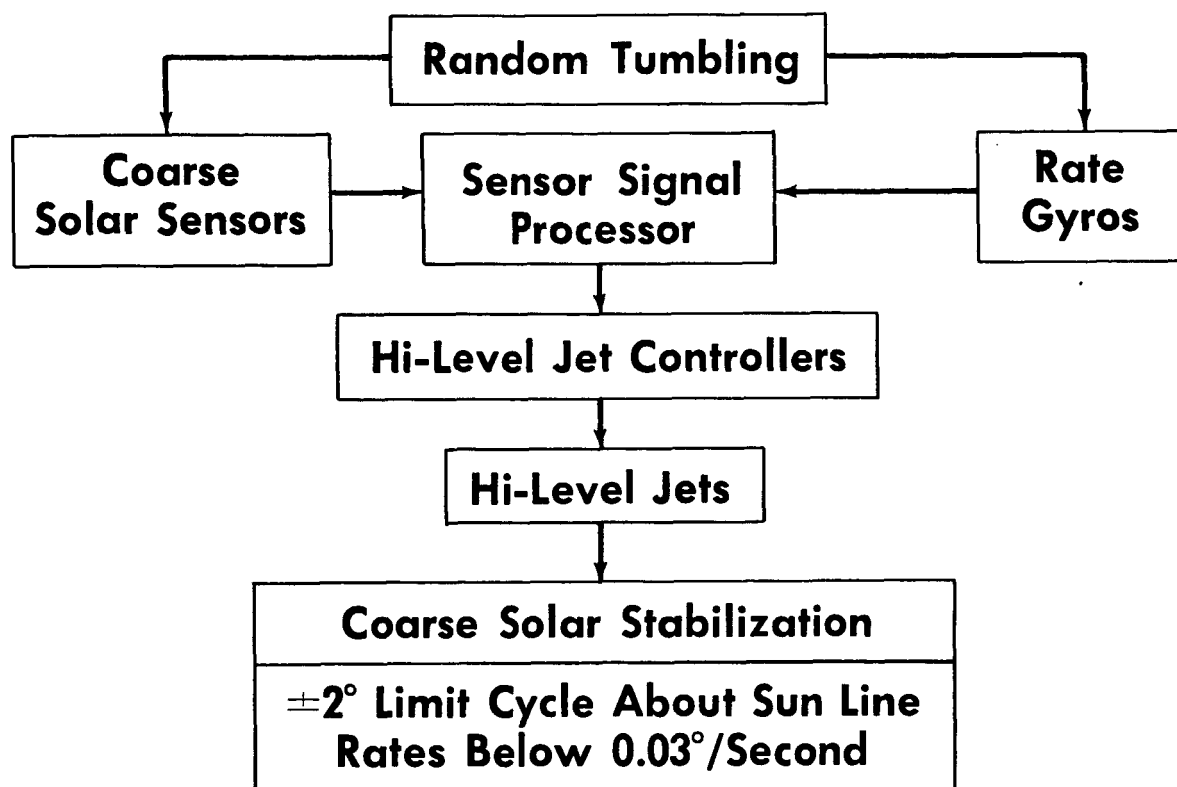


Fig. 4 Sensors and Actuators Used in Initial Stabilization and Orientation

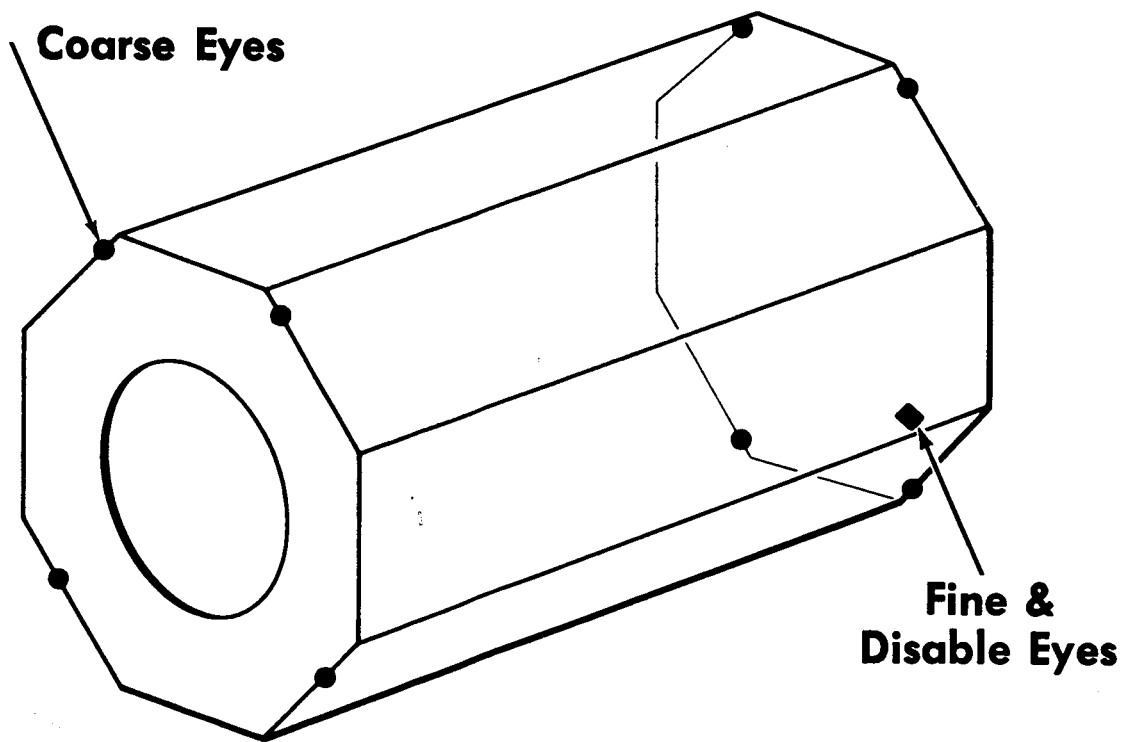


Fig. 5 Location of OAO's Eight Coarse Solar Sensors

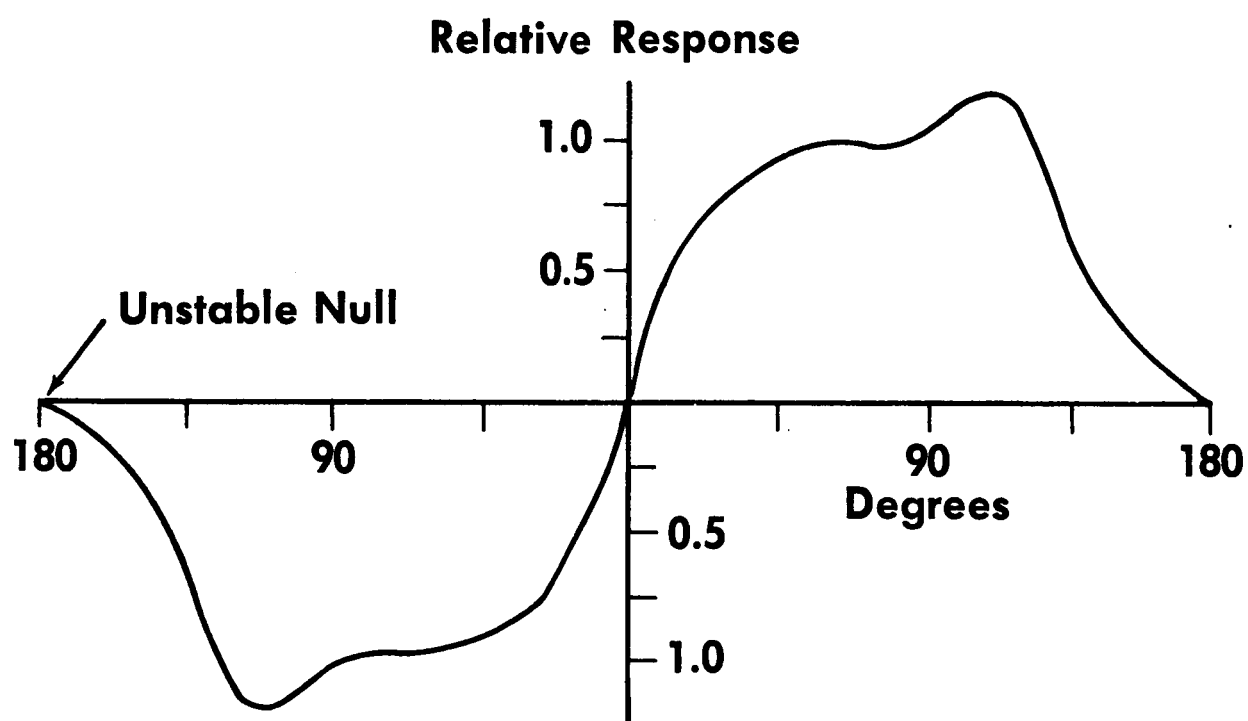


Fig. 6 Solar Sensor Response as a Function of Position

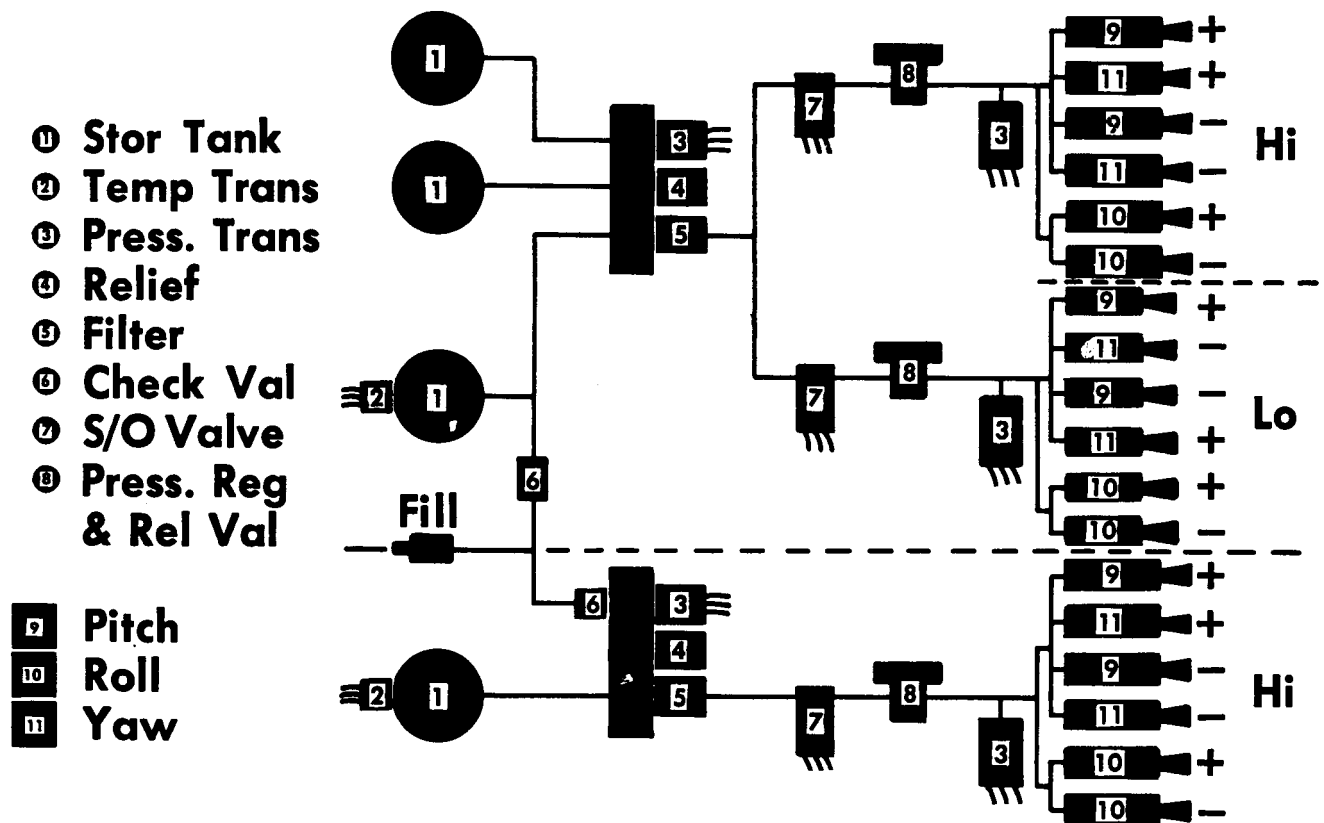


Fig. 7 Nitrogen Gas Jet System

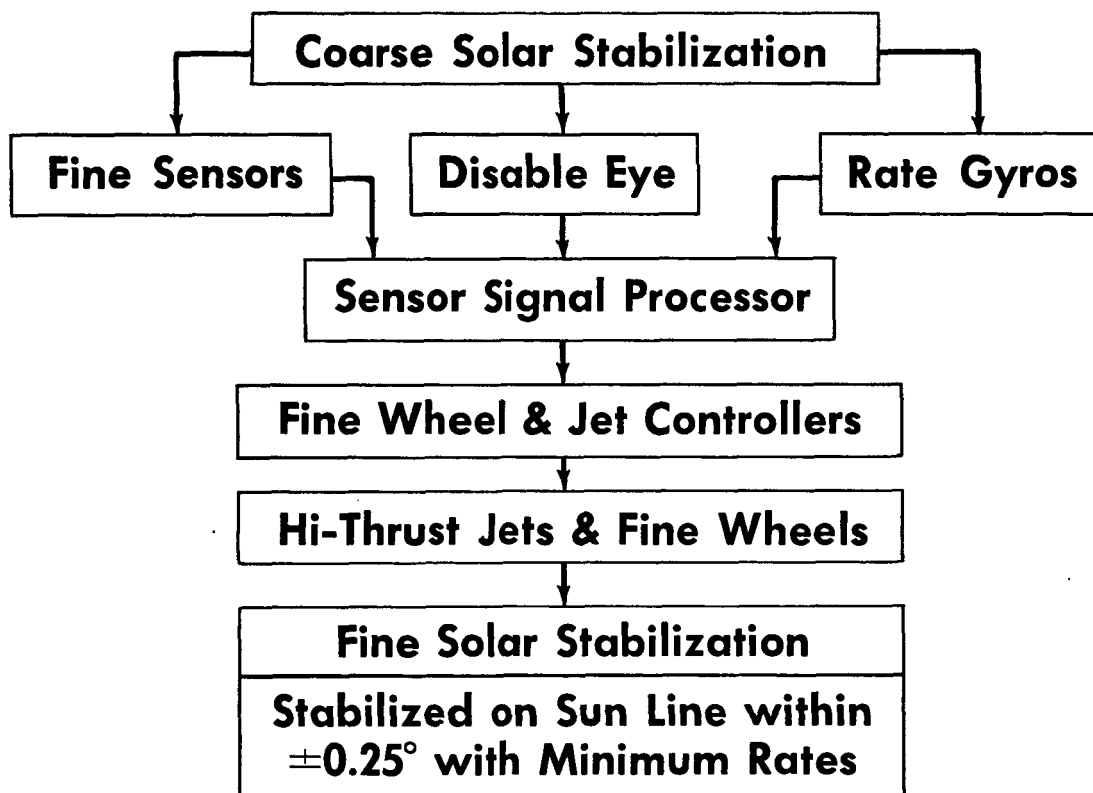


Fig. 8 Sensors and Actuators Used to Obtain Fine Solar Stabilization

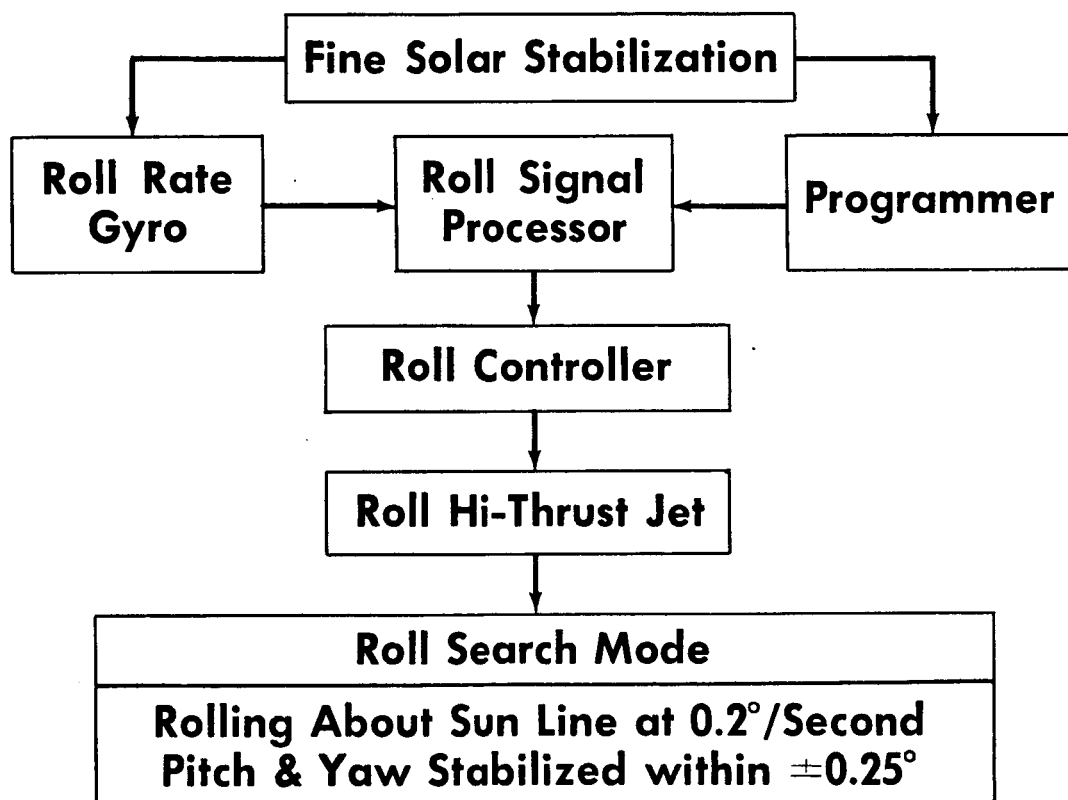


Fig. 9 Sensors and Actuators Used in Roll Search Mode

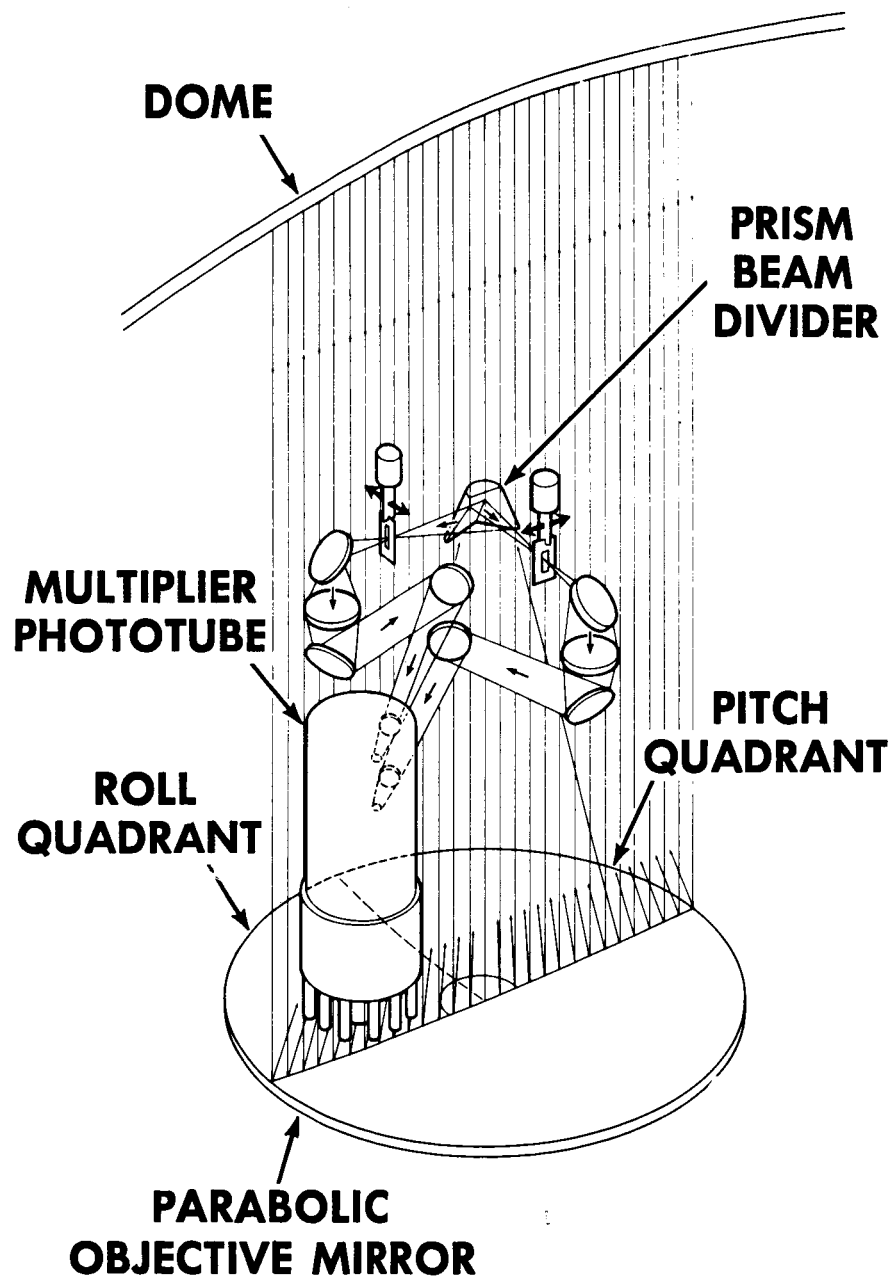


Fig. 10 Gimballed Star Tracker Optical System

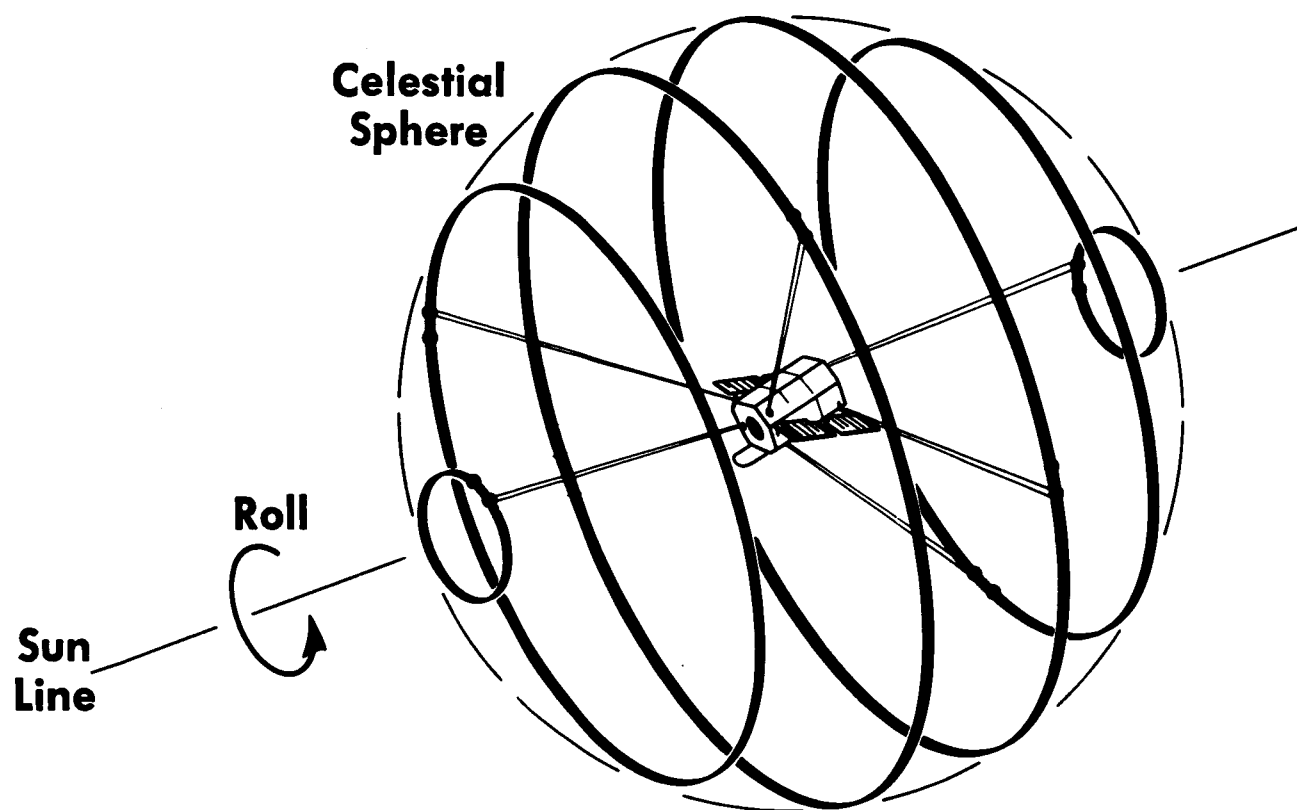


Fig. 11 Roll Search Mode for Star Tracker Acquisition During Initial Stabilization

### First Command Word

1	1	*	Execution Time
---	---	---	----------------

Memory Address	Command Class	Inertia Wheel	Unused
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### Second Command Word

1	1	CW/ CCW	No. of Rotations to TR
---	---	------------	------------------------

Total Rotations to Stop
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Fig. 12 Format of Pointing Commands

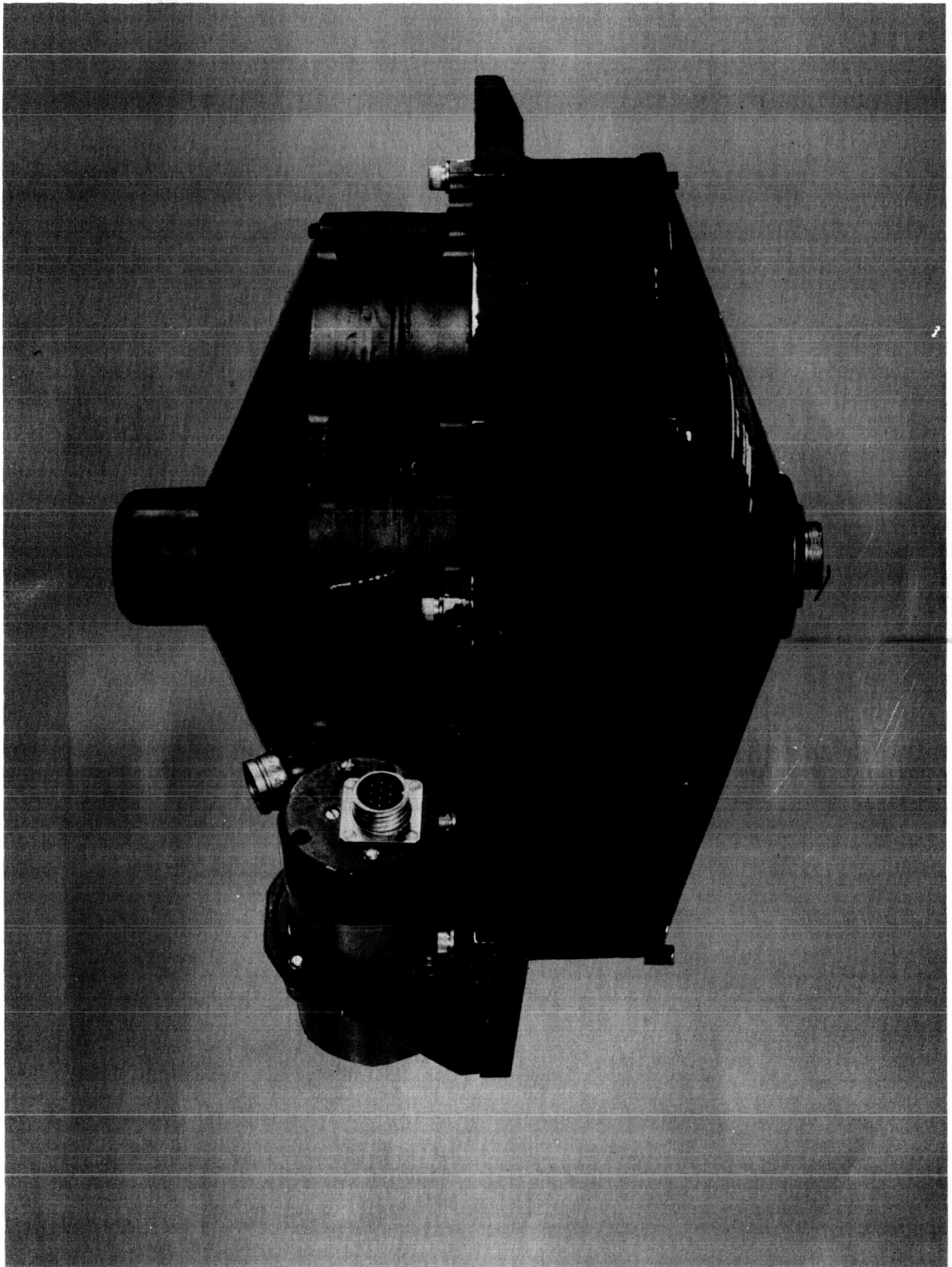


Fig. 13 OAO Inertial Wheel Package

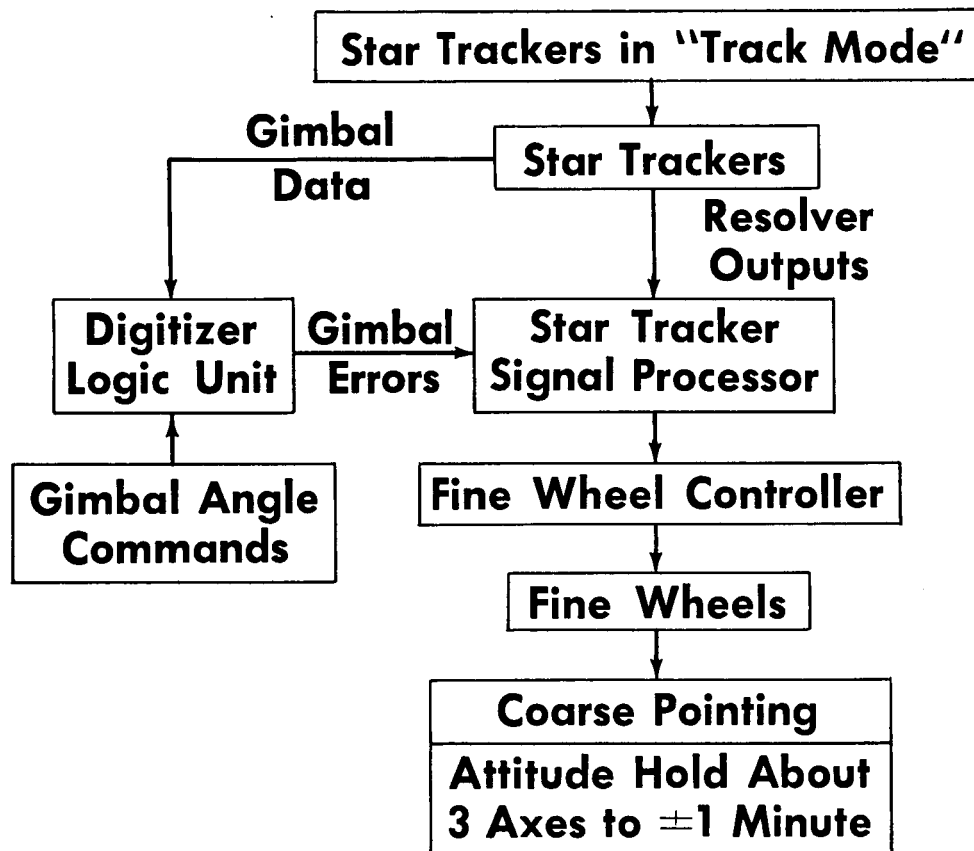


Fig. 14 Coarse Pointing Operation

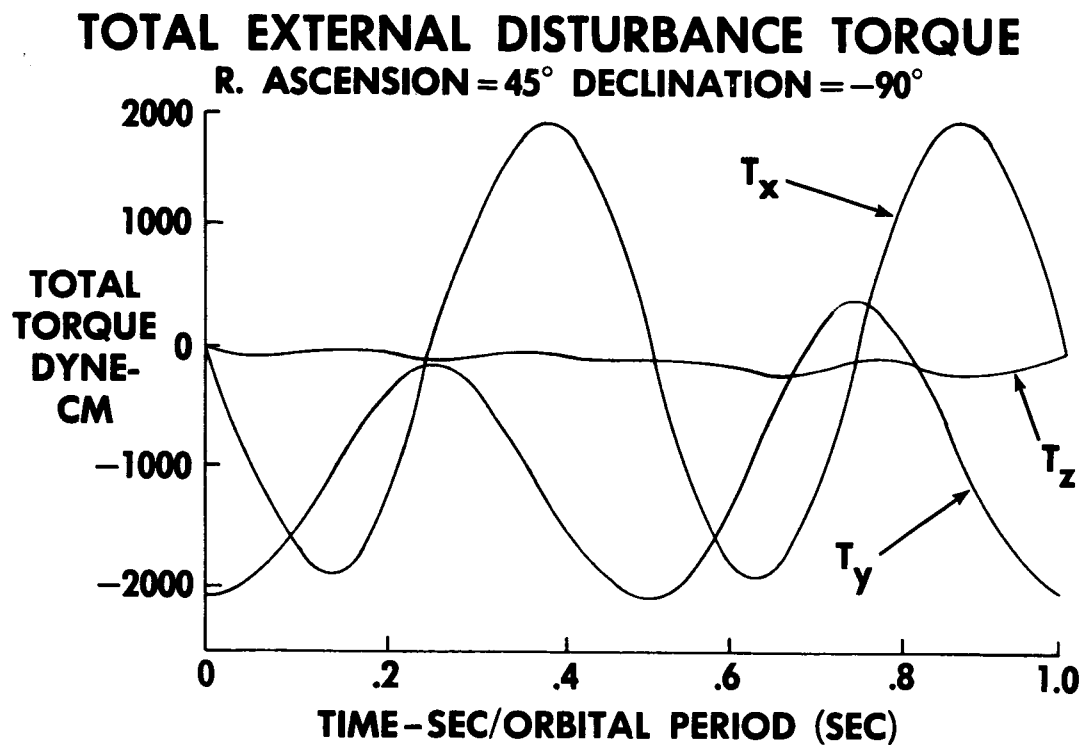


Fig. 15 Summation of External Disturbance Torques Acting on OAO

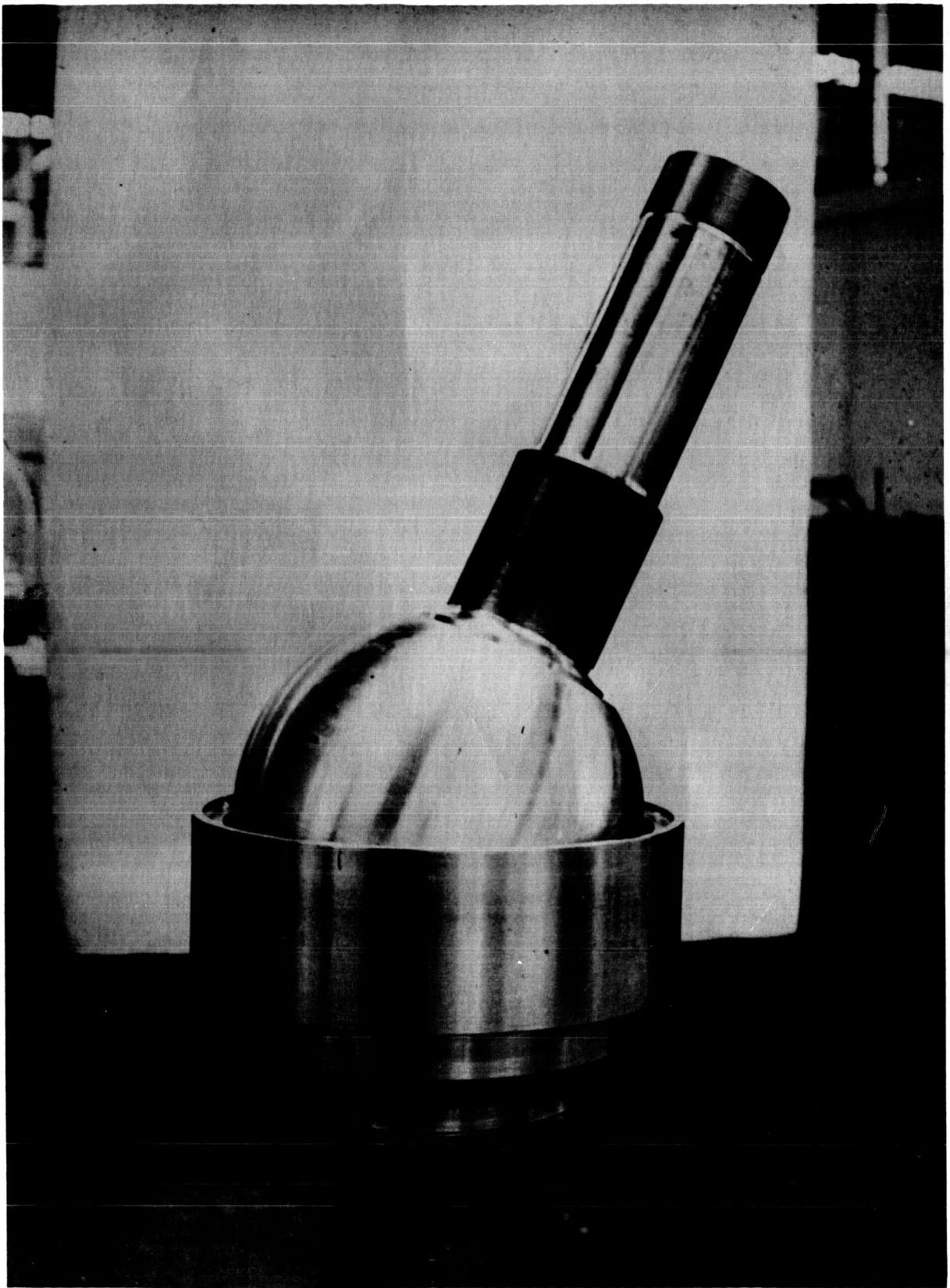


Fig. 16 Air Bearing Ball and Socket